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Determination of Densities of
RESERVOIR SEDIMENTS
In Situ With a Gamma Probe

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Growth Through Agricultural Progress

USDA Sedimentation Laboratory
Soil and Water Conservation Research Division
Agricultural Research Service
United States Department of Agriculture

DETERMINATION OF DENSITIES OF RESERVOIR SEDIMENTS *IN SITU* WITH A GAMMA PROBE[1]

by

J. Roger McHenry[2]

ABSTRACT

The attenuation of gamma emissions on passing through matter has been adapted for determining the densities, *in situ*, of reservoir sediments. The equipment is described, as well as the procedures for the necessary calibration of the detector instrument. The attenuation of gamma rays was found to be a linear (log) function of the density of the sediment. Excellent precision was obtained with the equipment described. The profile densities obtained on the Power Line Dam reservoir, Lafayette County, Mississippi, are shown as typical of the field data obtained during 2 years of investigation.

INTRODUCTION

The attenuation of gamma rays on passing through matter has been adapted for determining the density of materials. Many commercial and industrial adaptations are presently in use. The determination of soil and sediment densities by such techniques has been reported (1, 4, 5).[3] The experiences of the Sedimentation Laboratory for the past 2 years with a gamma probe in measuring densities of reservoir sediments are presented in this report.

THEORY OF OPERATION

The attenuation of a beam of gamma photons in matter follows the exponential relationship:

$$I = I_o e^{-\mu x} \qquad (1)$$

where μ is the macroscopic total cross section absorption, I_o the incident intensity, I the emergent intensity, and x the thickness or density of the absorber material. As used here, μ is the total linear absorption coefficient, which is the sum of the macroscopic cross sections for the three processes attenuating gamma photons: (1) The photoelectric effect, (2) the pair production, (3) the Compton effect. The mass absorption coefficient, C_m, is the ratio of the linear absorption coefficient to p, the density of the material, that is, μ/p.

The exponential equation (1) is valid only when the emitted gamma photons are monoenergetic and when the material being tested is homogeneous and hence possesses the same absorption coefficient. Where the values of $\mu_1, \mu_2, \mu_3, \ldots \mu_n$ exist because of differing photon emission energies or the composite nature of the absorber material, or both, proportional values of $I_1, I_2, I_3, \ldots I_n$ must be obtained and summed for the total attenuation.

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[1] Contribution from the Sedimentation Laboratory, Soil and Water Conservation Research Division, Agricultural Research Service, United States Department of Agriculture, in cooperation with the University of Mississippi and Mississippi State University.

[2] Soil Scientist, Sedimentation Laboratory, Soil and Water Conservation Research Division, Agricultural Research Service, USDA, at Oxford, Miss.

[3] Figures in parentheses refer to Literature Cited at end of this report.

The mass absorption coefficients, C_m, for elements with atomic numbers less than 25 ($Z<25$), with the exception of hydrogen ($Z=1$), are similar in value--ranging from 0.109 to 0.138 cm^2/g for 0.2 Mev photons (2). Of the 16 most abundant elements in the earth's crust, only hydrogen, iron, and barium have values of C_m exceeding 0.139 cm^2/g. Of these, barium is seldom found in soils or recent sediments in other than trace amounts. The value of C_m for iron is only slightly greater than the indicated range, that is, 0.146 cm^2/g. Hydrogen is an anomaly with a C_m value of 0.243 cm^2/g. The larger the value of C_m the greater is the attenuation power of the material for gamma photons. It appears possible to measure the water content of a material by means of differential gamma photon absorption. However, the proportion of hydrogen atoms by weight in sediments is small. The resulting attenuation of gamma photons due to the hydrogen atom concentration is only a small fraction of that associated with small changes in density. An accurate measurement of soil moisture would be dependent, therefore, on a constant density of the medium.

The determination of sediment density by gamma attenuation is practical since no common constituents of soils, and therefore sediments, in the Mississippi area, as elsewhere in the United States, exceed the atomic number of 26. The proportions of hydrogen, oxygen, silicon, aluminum, and iron, the most common elements comprising roughly 90 percent or more of most soils, will not vary sufficiently as to significantly change the mass absorption coefficient of sediment-water systems. For example, the C_m value of water is 0.136 cm^2/g and that of an average concrete is 0.124 cm^2/g; both being within the range of low atomic number elements.

Two techniques are in general use for determining the densities of materials by gamma-ray attenuation. The transmission, or two-probe, system (4, 5) employs two probes; one contains a source of gamma radiation, the other a radiation detection device, usually a scintillation crystal. Density of the material between the two probes is measured using a constant experimental set-up, or geometry. The attenuated gamma readings can be converted directly to density readings. Discrimination of the energy of the emissions with a pulse height analyzer is possible also with a gamma scintillation spectrometer so that secondary or scattered radiations, that is, emissions with reduced energy, are not detected. In addition to this discrimination ability, the two-probe system employing a scintillation spectrometer permits the measurement of the density of thin (1 to 2 inches) horizons by collimating the beam of gamma photons.

The second method of determining the density of sediments and/or soils is with a single probe in which the source is separated from the detection system by lead shielding (1, 3). In operation the single probe measures the attenuation of gamma photons, as well as the attenuation of secondary radiations, which are scattered by collisions with atoms of the material after emission from the source and which are reflected, or deflected, to the detection system. If a constant geometry is maintained, that is, a constant distance from source to detector in materials of similar absorption coefficients, the attenuation of the fraction of reflected and scattered photons reaching the detector system can be expressed as a function of the density of the system into which the probe is placed.

The single probe method of determining density, it must be remembered, is empirical in nature as the absorption coefficients of atomic species increase considerably as the energy of the gamma photons decreases, that is, as the photons lose energy on scattering. However, the nature of most sediments are similar enough that empirically determined calibration curves are applicable over a wide area, geologically and geographically.

LABORATORY INVESTIGATIONS

Instrumentation

The gamma probe employed in this study is of the single probe type. The gamma probe, as presently used, is shown in Figure 1 together with accessory equipment

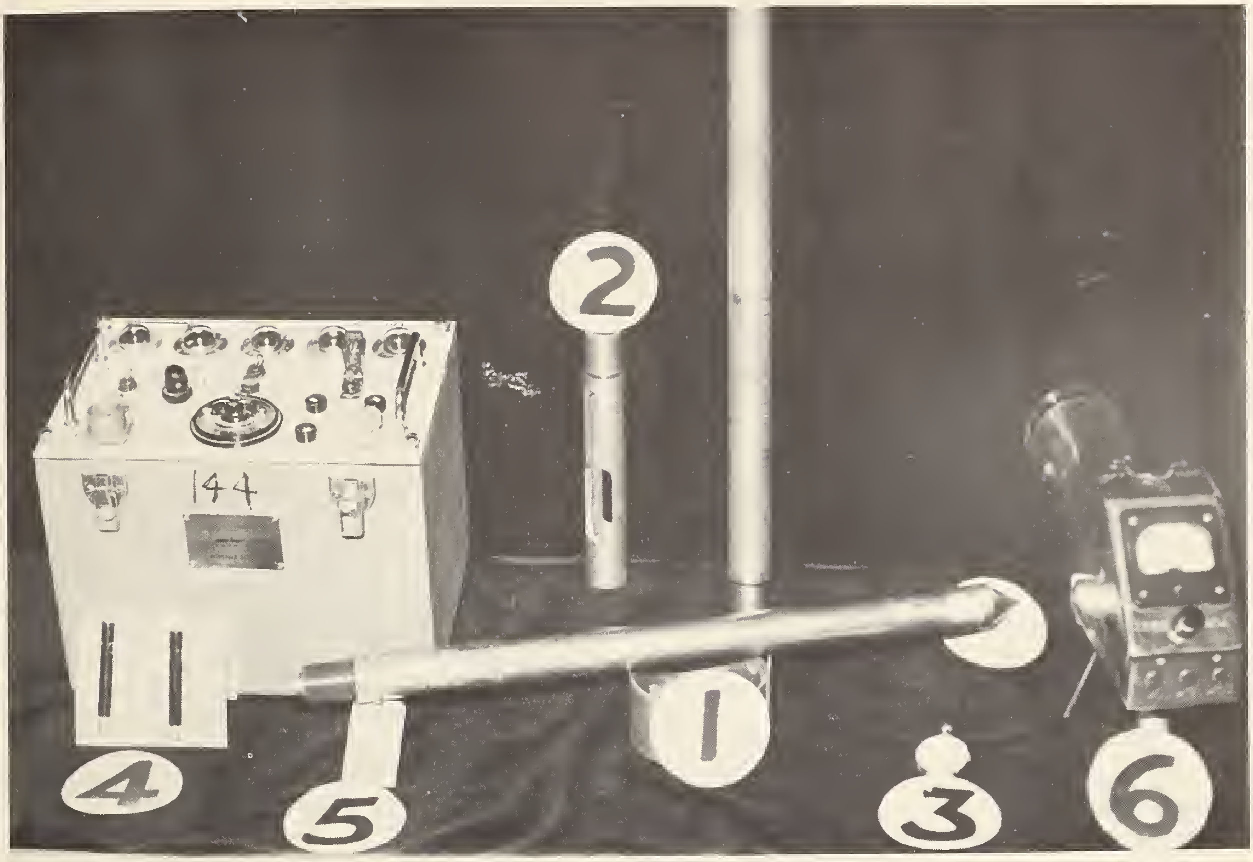

Figure 1.--A gamma probe and accessories necessary for operation: 1, Probe containing radioactive source, shielding, detector tubes, and preamplifier; 2, connecting section with aluminum tubing to the right; 3, stopwatch; 4, personnel exposure pencils with portable scaler behind; 5, film badge; 6, survey meter.

including a Nuclear-Chicago Model 2800 portable scaler. The gamma probe was manufactured under contract by Technical Operations, Incorporated, according to Beach Erosion Board specifications (1). Modification of the original design, essentially a streamlining of the exterior container, has been made by the Beach Erosion Board (1) and the Agricultural Research Service. The source, approximately 3 millicuries of radium-226, is located near the tip of the probe (see Figure 5). The source is separated from the three Geiger-Mueller tubes used to detect the gamma radiations by 6 inches of lead. The GM tubes are connected to a transistorized preamplifier circuit and the signal from the preamplifier is read out on a portable scaler, Nuclear-Chicago Model 2800.

Calibration

The calibration of the gamma probe was accomplished in the Sedimentation Laboratory in the following manner: standard 55-gallon steel drums were filled with the desired proportion of water and soil material from the area of study and, after mixing thoroughly, the attenuation of the gamma photons was measured. Subsequent additions of water and/or soil produced additional values.

The calibration curve obtained with north Mississippi soil material--Grenada clay loam--is shown in Figure 2. The points at either end of the calibration curve, from 0 to 10 lbs./cu.ft. or from 60 to 75 lbs./cu.ft., were readily obtained by mixing water and soil. The suspensions containing 60 lbs./cu.ft. and more of sediment were viscous enough that no significant settling of sand was observed on standing. The suspensions containing

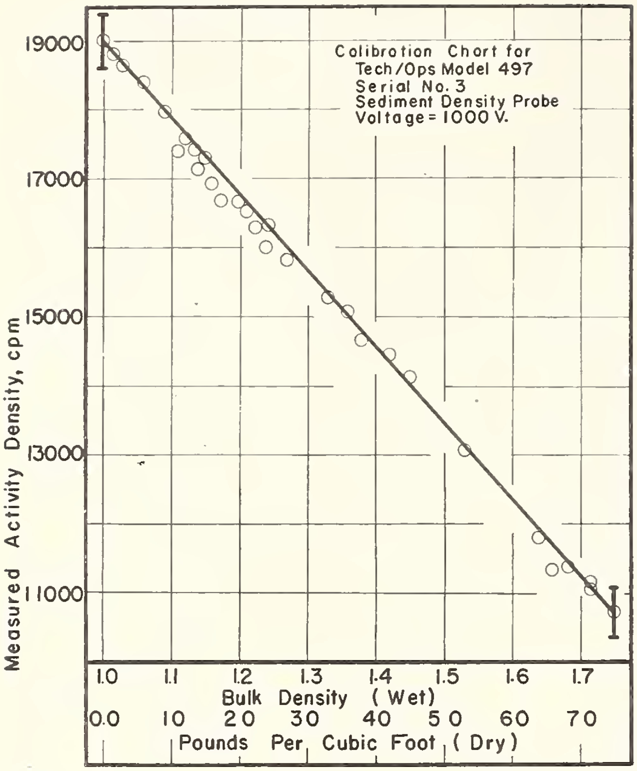

Figure 2.--Calibration curve for a gamma probe. The measured activity density is plotted as a function of the density of the sediment-water system. The calibration curve is represented by the equation: $Y = 30{,}067 - 11{,}067\ X$.

less than 10 lbs./cu.ft. were sufficiently dilute that settling of the sand fraction did not affect the measured values significantly. It was found desirable to add bentonite, or sediments exceptionally high in clay, to suspensions containing 10 to 60 lbs./cu.ft. of sediment. These additions provided sufficient viscosity to the suspensions that settling of the larger particles did not affect significantly the measurement of density by gamma-ray attenuation. In cases where the material under test contains adequate amounts of clay, the addition of bentonite material would be unnecessary.

Effective Volume

The measurement of sediment density, by the attenuation of gamma rays, is a function of the mass of the material present as well as of the density if the mass is less than infinite insofar as the range of the scattered gamma photons is concerned. If the mass is infinite, or sufficiently large to be so considered, the attenuation of gamma photons noted is not altered by changes in volume of the material and is a function only of the density of the material. Caldwell (1) indicated that the volume of water equivalent to that in a standard 55-gallon steel drum is not sufficiently large to be considered infinite, as an increase in this volume produced a change (increase) in the measured gamma activity. Insofar as the measurement of the density of water is concerned data collected in the Sedimentation Laboratory substantiate this conclusion. However, when a suspension of sediment is examined a different conclusion is obtained. In figure 3 the densities of sediment suspensions, obtained in a 55-gallon steel drum with a 22-inch diameter, are compared with those obtained in a 48-inch diameter tank. Although only a limited number of readings were taken the observed differences are not significant. In 4 of the 6 paired sets of measurements the difference is less than that assignable to statistical randomness of radioactive decay, that is, less than the value of the standard error. For practical purposes the volume of a suspended sediment, 10 lbs./cu.ft. or greater, in a 55-gallon steel drum, 22-inches in diameter, is infinite. A calibration curve relating density to gamma-ray attenuation and obtained by using such a container is assumed applicable to field conditions. Some error in the field use of this calibration may occur but, within the accuracy of the method, which is about 1 percent because of the randomness of radioactive decay, the reported values are a true measure of the sediment density.

A number of variables may influence the relationship of gamma-ray attenuation to density. Caldwell (1) has considered a number of these as: Effect of submergence of the probe, proximity of walls, temperature, and amplifier voltage. Each of these variables was considered. In all measurements the probe was fully submerged in the media. No measurements were taken closer than 10 inches to a container wall; the bottom of the probe was at least 6 inches from the container bottom, because it was found that lesser distances influenced the measurements of gamma-ray attenuation. Voltage was maintained constant at the level suggested by the manufacturer for the particular gamma probe. Temperature does not influence radioactive processes. Within the working limits of the study, the electronic components were similarly unaffected. With these precautions none of the variables was found to affect significantly the relationship of gamma attenuation to sediment density.

The volume of the sediment, whose density is expressed by the scaler reading, is considered to be spheroid in shape. The maximum dimensions of this volume approximate 18 inches in height by some 20 inches in diameter--the sediment within a smaller spheroid is responsible, however, for most of the observed gamma attenuation. In water the effective volume of the spheroid is somewhat larger as has been indicated above. A characterization of the vertical distribution of areas of similar sensitivity about the gamma probe was attempted. Measurements of gamma-ray attenuation were taken as the gamma probe was lowered from air into water in successive increments. The results are plotted in Figure 4. The change in measured activity density per increment of immersion as c.p.m. is plotted as a function of the depth of immersion of the gamma probe.

As the tip of the gamma probe entered the water a rapid increase in the observed count rate occurred. This was due to the increased production of secondary and scattered radiation in the more dense medium, water. The increase in the differential count rate continued until the source was fully submerged at about 4 inches. On further immersion the total count rate continued to increase but the differential count rate per unit of immersion decreased. This is due to the increasingly greater attenuation of the gamma beam in water as the depth of immersion increases. When that portion of the probe containing the lead shield was submerged completely, that is, 10 inches, further immersion again produced an increase in the differential count rate. This increase in differential count rate is attributed to the submergence of the GM detecting tubes. With the submergence of most of the GM tube a decrease in differential count rate occurred. The peak differential count rate during the time the GM tubes were being immersed, i.e., the maximum change in count rate/unit immersion depth, was taken as the center of sensitivity of the GM tubes and arbitrarily selected as the center of sensitivity of the gamma

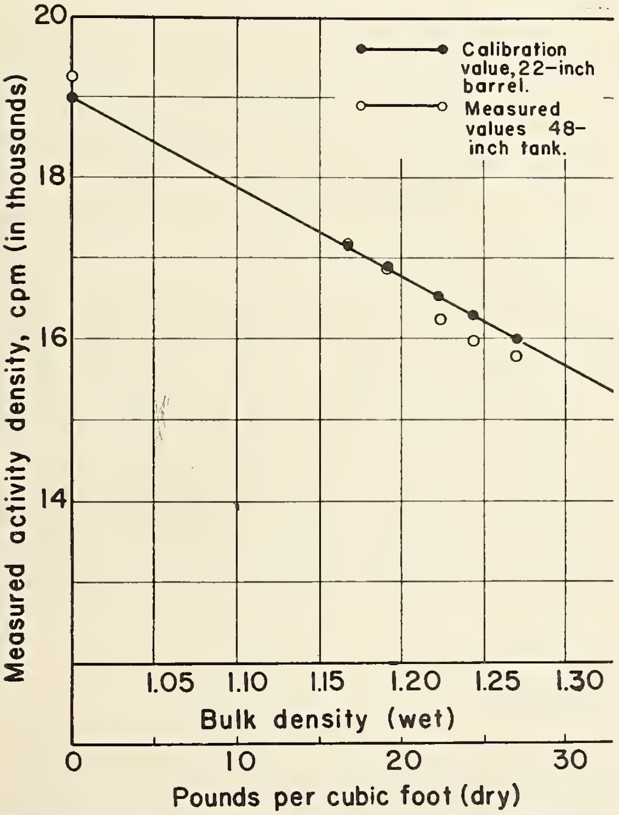

Figure 3.--The measured activity density plotted as a function of sediment density contained in (1) a 22-inch diameter container and (2) in a 48-inch diameter container.

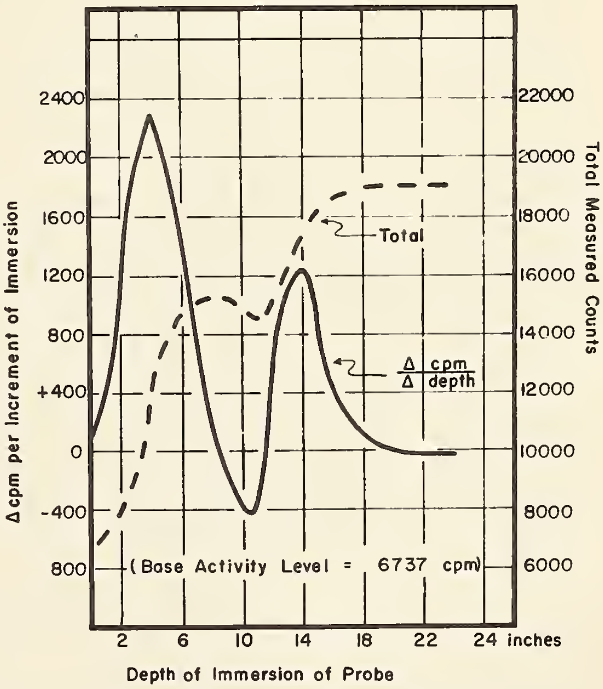

Figure 4.--The differential change in measured activity density per increment of immersion plotted as a function of the depth of immersion of the gamma probe. The total activity density is also included.

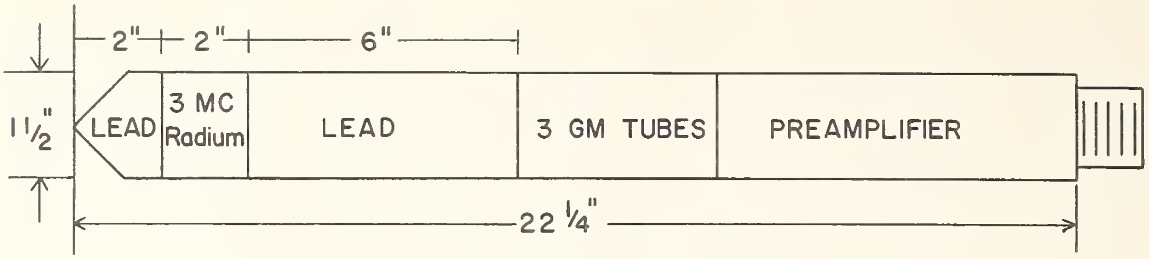

Figure 5.--Schematic layout of a gamma probe.

probe. This point was 14 inches from the tip of the probe. This corresponds to the point of inflection of the differential count rate curve in Figure 4 and to the center of the detection tubes. Further immersion resulted in a greater total count but the differential count rate greatly lessened per unit of submergence. After 18 inches of the gamma probe was submerged a constant count rate was observed indicating that the spheroid of the effective volume was all below the surface of the water. Consequently, all measurements in this study were made with 18 inches or more of the probe submerged. A sketch of the probe showing the approximate dimensions and locations of the various parts is shown in Figure 5.

Discussion

The results shown in Figure 4 indicate an inherent weakness of the gamma probe in its present state of development. The density of a spheroid some 18 inches in height by 20 inches in diameter is known from any one measurement--this is an integrated density of the spheroid volume with that material closest to the source and to the detector tubes contributing most. Densities of layers of less thickness can, at best, be only approximated. The material surrounding the 8-inch portion of the probe containing the detector tubes contributed about 5000 counts, whereas the remaining 10 inches contributed 7000 counts. Because of this distribution of sensitivity throughout the length of the probe, any attempt to obtain exact measures of sediment density for layers of less than 16 inches is difficult when using the gamma probe. It is possible to take successive density measurements with corresponding increments of depth of penetration of the probe in sediments and to determine with some degree of precision the relative densities of successive layers less than 16 to 18 inches in thickness. Each of these measurements is confounded with the density of the material above and below the measuring increment employed. For example, densities have been made at 6-inch vertical intervals and reported in this study. The center of this 6-inch section is arbitrarily taken as the center of the detection tubes or at the upper inflection point in the curve in Figure 4. Each such reported density is influenced by the material outside the 6-inch horizon reported, particularly that lying below the 6-inch section. However, a major contribution to the measured gamma-ray attenuation is properly ascribed to the 6-inch layer. Whenever three or more successive layers yield equivalent readings, the densities are comparable, of course, on a quantitative basis.

FIELD STUDIES

The gamma probe was employed extensively by the Agricultural Research Service for sediment density measurements during 1959 and 1960. In 1959 the probe was employed as originally designed by the Beach Erosion Board (1) and the calibration curve supplied by the manufacturer was used. The modified version of the gamma probe was employed for all measurements made in 1960. The field data reported here were collected in Mississippi in 1960 and are presented as being typical of much more extensive data.

A small dam was constructed by the Soil Conservation Service on a tributary of East Goose Creek in Lafayette County, Mississippi, in 1953. The particular reservoir has been designated the "Power Line Reservoir". Ranges and elevations were established in 1953 and resurveys were made of the established ranges in 1958 and 1960. Measurements of the density of the sediment were made with the gamma probe in 1959 and again in 1960. Densities of sediments were determined for selected ranges at predetermined locations. At each location the density of a vertical profile was measured. At each location the gamma probe was lowered in 6-inch increments and measurements of density made. As noted above, the activity measured by the gamma probe is most affected by the material immediately about the probe. Thus the readings reported at 6-inch intervals are subject to the influence of the material existing above and particularly below this layer.

Typical of the measurements of density made on "Power Line Dam" are those shown in Figures 6 through 9. The original (1953) range line profiles and the present (1960) sediment depths, as determined by hand sounding methods, are shown. The vertical differentiation of the density profile measured with the gamma probe is illustrated graphically. In the figures the extension of the vertical profile below the lowest measured density (that is the white area below the shaded portion) represents the extension of the probe beyond the 6-inch spheroid centering about the sensitive point of the gamma probe. In only a few instances did the gamma probe appear to penetrate the original material. The gamma probe is pushed into sediments by hand; no driving mechanisms are employed. The extension sections, 6-feet long, are of aluminum tubing and this, together with the thinness of the stainless steel jacket of the probe itself, prohibits driving the probe into the sediments.

Densities of sediments were observed to range from essentially that of water to over 75 lbs./cu. ft., dry-weight basis. Materials deposited in the deeper parts of the pool (Figure 7), or where considerable overburden occurred (Figure 9), showed the greatest densities. The existence of a zone of "fluid" sediment over consolidated sediment is shown in Figure 8. For example, the profile at 180 feet showed an increasing sediment density in a zone almost 30 inches deep above the consolidated sediment level as measured by hand sounding methods. As the sensitive length of the gamma probe is 18 inches, a considerable depth of unconsolidated sediment is indicated.

The hand sounding method employed at this reservoir located the depth of consolidated materials but was insensitive to suspended or "fluid" sediments. The sounding rod employed had a diameter of only 1 inch so that penetration of liquid and semi-liquid sediments would occur with no indication to the operator of their presence. The gamma probe is unique in that the densities of these unconsolidated sediments are as readily measured as are those of the consolidated sediments.

The densities of the "fluid" sediments above the consolidated material in the 180 feet profile, Range J-K (Figure 8), may appear high. The density of the first 12 inches of material above the consolidated sediment is, of course, influenced by the consolidated sediment as the probe is partly in the consolidated sediment when the center of the sensitive volume of the probe is at these depths. Readings taken when the center of effective volume is greater than 12 inches from the consolidated sediment are unaffected. Densities to 60 and 70 lbs./cu. ft. were obtained. These density values are high. However, in the two adjacent vertical sections, 160 to 220 feet, as well as elsewhere on this range (275, 300, and 310 feet verticals), similar results were obtained. It is possible, of course, that the density readings were obtained at slightly different points than the corresponding soundings. The limits of error of location are, however, rather limiting. The large discrepancies in the depths of sediments detected could be resolved on the assumption the "fluid" sediments are dense but liquid and that the sounding rod employed was insensitive to "fluid" sediments. When the gamma probe was calibrated, mixtures of sediment and water containing 50 to 70 lbs./cu. ft. dry weight were not consolidated. The viscosity was high but a sounding rod of the type used would penetrate the mixture. This particular point is one for further study.

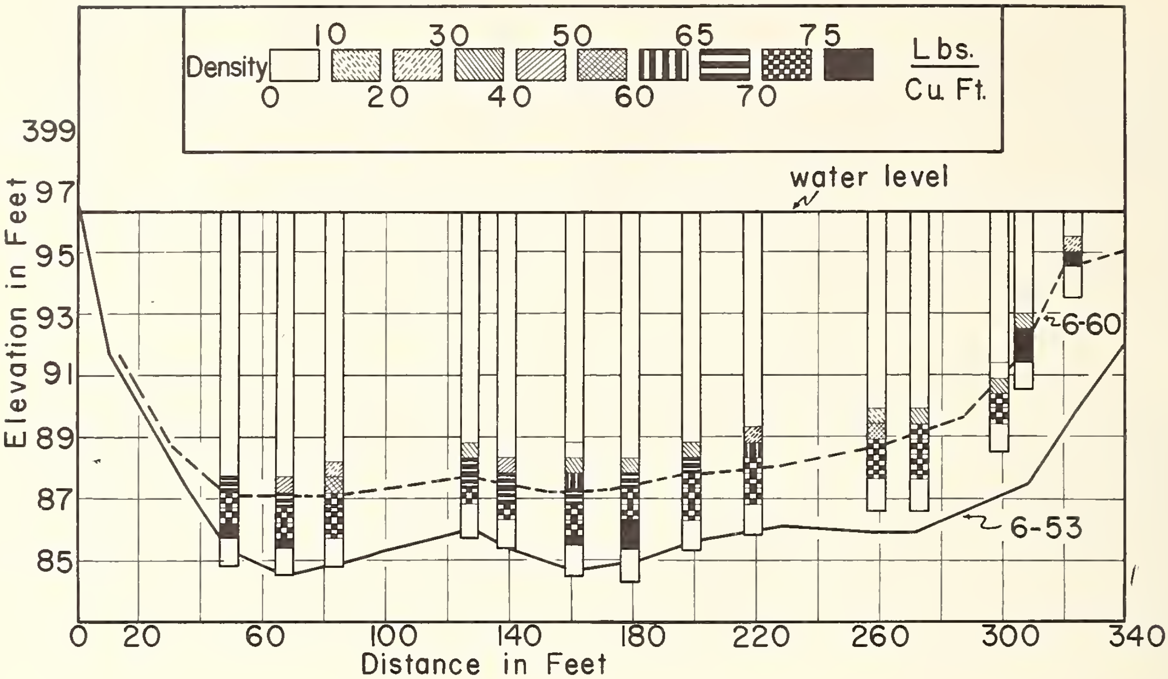

Figure 6.--Sediment density, Range O-I, Power Line Dam, Lafayette County, Mississippi, 1960. (NOTE: The white area immediately below the shaded areas in each vertical profile indicates the extension of the gamma probe beyond the center point of the lowest recorded density measurement.)

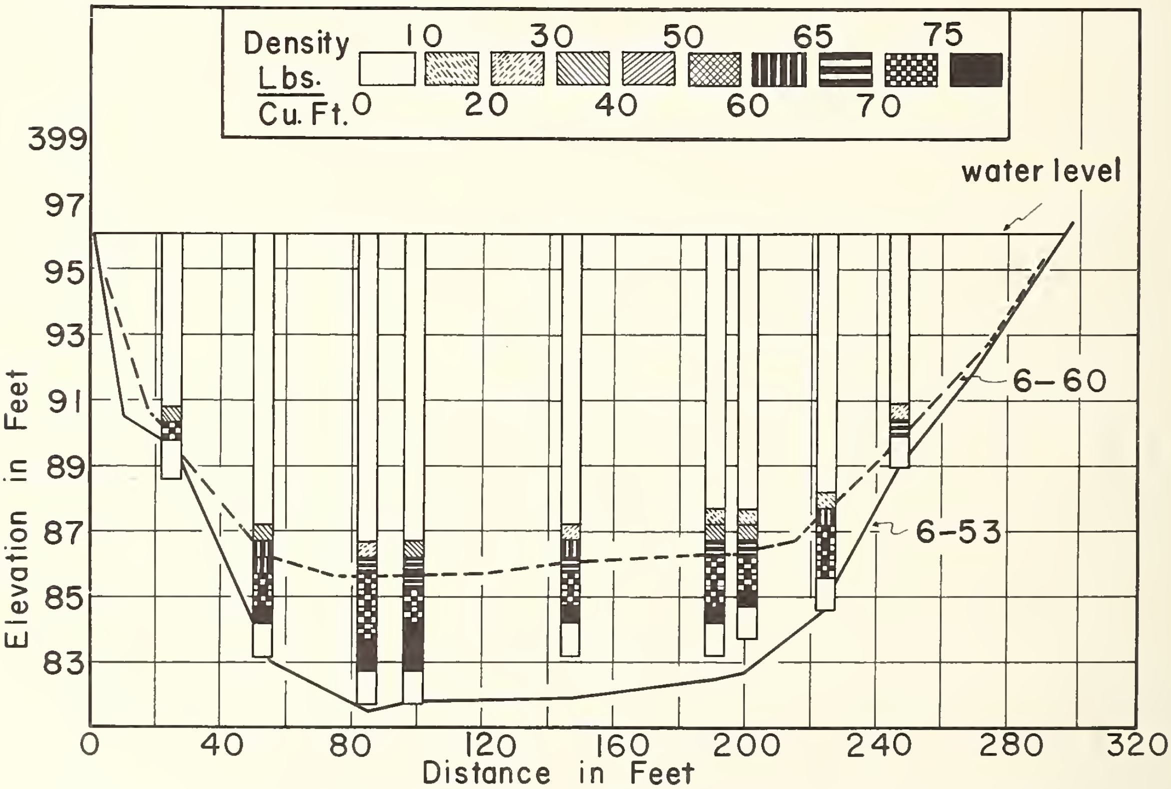

Figure 7.--Sediment density, Range N-M, Power Line Dam, Lafayette County, Mississippi, 1960.

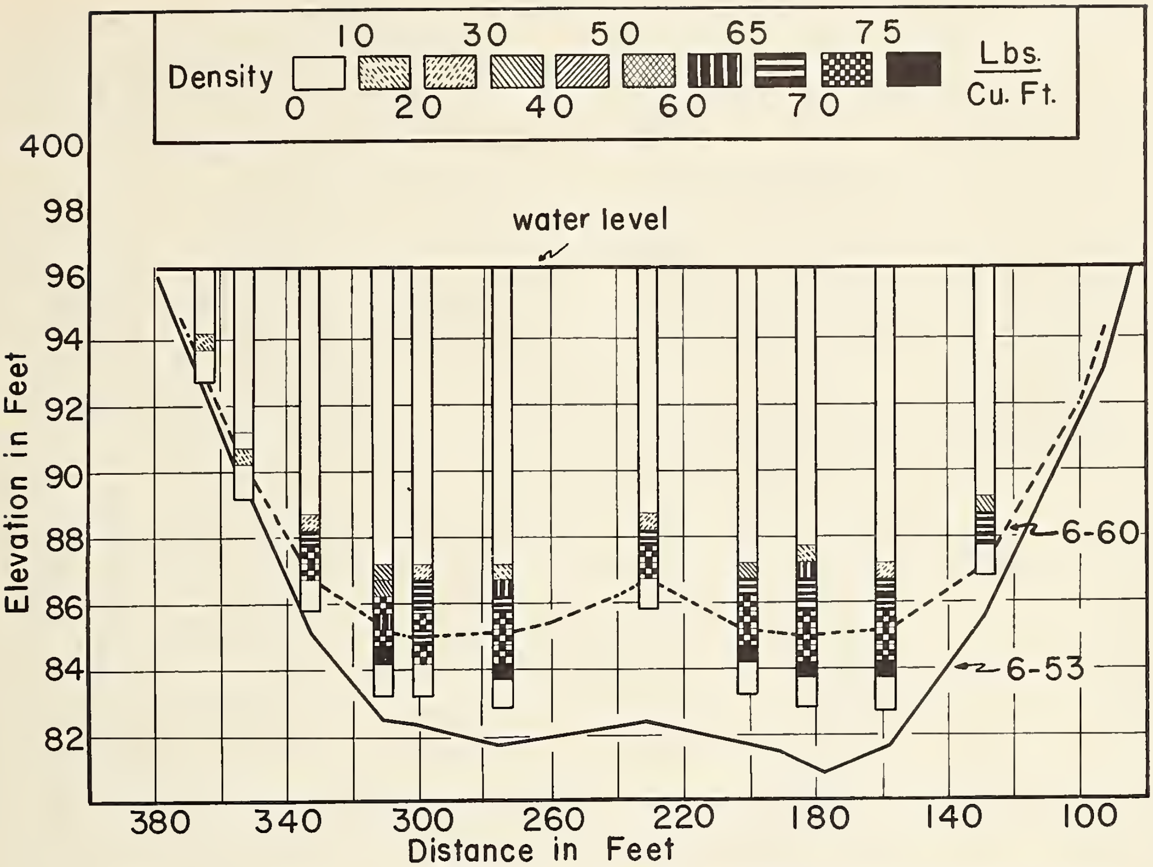

Figure 8.--Sediment density, Range J-K, Power Line Dam, Lafayette County, Mississippi, 1960.

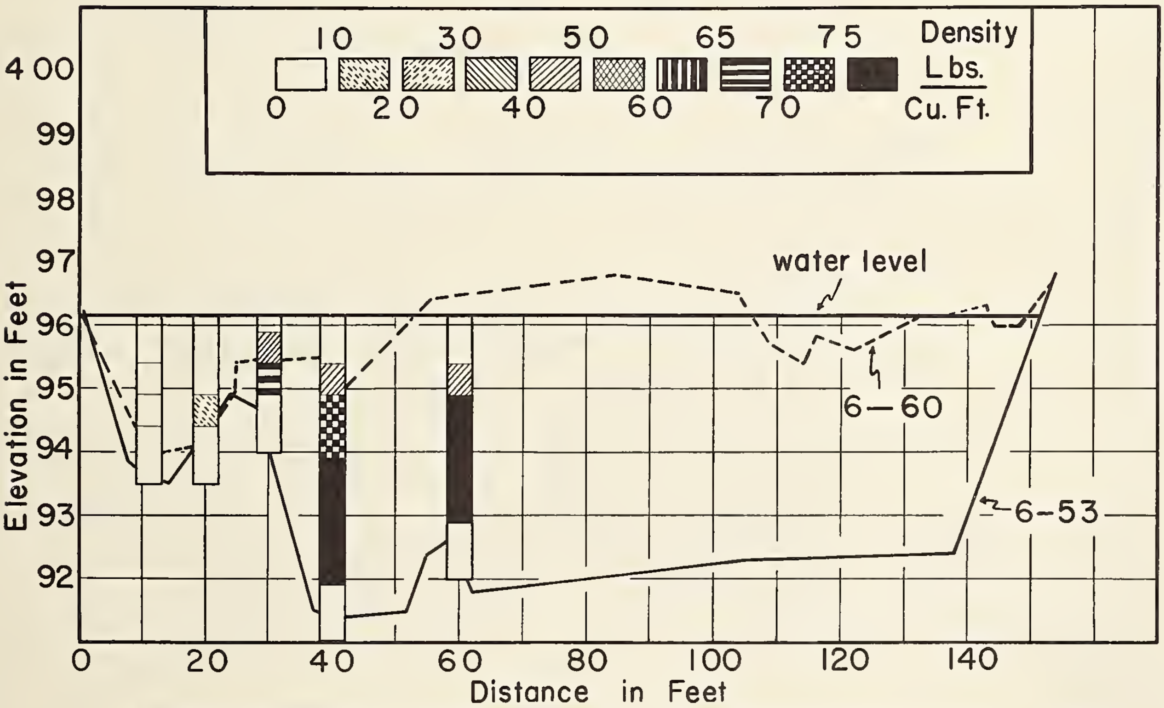

Figure 9.--Sediment density, Range M-L, Power Line Dam, Lafayette County, Mississippi, 1960.

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A number of pertinent observations concerning the depth, density, and location of sediment in the reservoir; the slope of the sediment level and the topography of the sediment in relation to land configurations can be made on the basis of these data, but they are considered beyond the scope of this report. The same may be stated concerning the development of suitable methods for handling the gamma probe and equipment in the measurement of reservoir sediment densities.

SUMMARY AND CONCLUSIONS

The determination of densities of reservoir sediments in situ by measuring the attenuation of gamma rays passing through the sediment has been investigated. In these studies the gamma probe as originally manufactured by Technical Operations, Inc., according to Beach Erosion Board specifications, and subsequently modified, was evaluated for use in reservoir sediment deposits. The gamma probe was utilized in a number of surveys of reservoir sediment density following necessary laboratory characterization studies, including calibration.

The gamma probe, in its present form (Figures 1 and 5), measures the density of sediments as a linear (log) function of the attenuation of gamma rays. Excellent precision is obtainable with the present instrument. In operation the gamma probe depends on the scattering of the emitted gamma rays and the attenuation measured is not of the emitted photons but of scattered and secondary emissions. Therefore the relationship measured is empirical because the exponential law of absorption is not followed. Calibration of the system is necessary in order to relate the empirical results to the desired end, that is, attenuation to changes in density.

Because the Geiger-Mueller detection tubes are separated from the radioactive source by 6 inches of lead, in order that all measured photons pass through the material under test, density determinations of layers less than 16 to 18 inches are not feasible except under special conditions. Despite this disadvantage the gamma probe provides a unique and reliable method for measuring reservoir sediment densities in situ. Sediments need not be consolidated--the gamma probe works equally as well in unconsolidated sediments.

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